Water Challenges for a Changing World
Joint Programming Initiative

Report on
Hydro-Meteorological Forcing

Work package 3:
Hydrometeorological Data

MUFFIN: Multi-scale Urban Flood Forecasting

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1. Introduction

This report provides an overview of the hydro-meteorological forcing data available for Work Package 3 of the MUFFIN - Multiscale Urban Flood Forecasting project.

Meteorological data - both observations and predictions - are collected at different spatial and temporal scales over the study areas. They are used as inputs to the hydrological models in the framework of the joint experiments to investigate crucial aspects related to the impacts of rainfall accuracy, spatial and temporal resolution and forecast lead time on the large and small scale flood forecasting in urban areas.

Both real-time (R) and historical (H) forcing data are being collected. Data are divided in two main categories, depending on whether they are observations (O) or predictions (P):

1. Observations (O):
   These include in-situ measurements by various types of weather stations (mostly rain gauges) and remote-sensing instruments such as weather radars and satellites, as well as merged products combining the measurements of two or several sensors (e.g., bias-corrected radar rainfall estimates using rain gauges).
2. Predictions (P):
   These include the output of numerical weather prediction models, radar rainfall nowcasts and synthetic rainfall fields generated by stochastic rainfall simulators.

2. Real-time and historical data

2.1. In-situ measurements

In-situ measurements are collected by weather stations on the ground at variable temporal resolutions. Information about rainfall is derived from automatic rain gauges and disdrometers. As a side project, TUD also collects data from citizen scientists in the greater Rotterdam area. The latter are of lower quality and reliability but can provide useful additional insight into the spatial distribution of rainfall after a flood to overcome the relatively low spatial density of professional rain gauge networks.

Domain	Sensor type	Measurements	Resolution	Availability
Rotterdam	1 KNMI weather station	Precipitation, Temperature, Pressure, Wind	10/60 min	1950 - present
Rotterdam	9 local TU Delft weather stations	Precipitation, Temperature, Wind	5 min	2012 - present
Rotterdam	>700 Netatmo Citizen Rain Gauges	Precipitation	5 min	2017- present
Stockholm	11 local rain gauges	Precipitation	15 min	2000 - 2014
Sweden	750 weather stations operated by SMHI	Precipitation, Temperature, Wind	15 min, 24 h	1961 - present
Finland	5 FMI automatic weather stations	Precipitation, Temperature, Wind	10 min	2010 - present
Helsinki	3 local rain gauges	Precipitation	1 min	2017 - present
Aalborg	7 WPC rain gauges	Precipitation	1 min	1979 - present
Aalborg	9 rain gauges (BEWARE)	Precipitation	1 min	2013 - present
Copenhagen	73 rain gauges from the WPC network	Precipitation	1 min	1979 - present
Europe	>7000 weather stations	Precipitation, Temperature	24 h	1950 - present

Table 1: available in-situ measurements within the MUFFIN experiment

Netherlands: The Royal Meteorological Institute of the Netherlands (KNMI) operate a professional automatic weather station at the airport of Rotterdam. Hourly data are available for free at http://www.knmi.nl/nederland-nu/klimatologie/uurgegevens. The high-resolution 10 min data are available upon request to TU Delft. In addition to the professional stations, TU Delft operates 9 local weather stations of type Campbell at different locations throughout the city of Rotterdam. These are semi-professional stations maintained on a monthly basis but the quality is lower than that of the professional KNMI stations. The collected data are available for free at http://weather.tudelft.nl/csv. In addition, TUD collects 5-min rainfall data from more than 700 citizen rain gauges of type Netatmo (https://www.netatmo.com/) in a radius of about 50 km around Rotterdam. Citizen rainfall data are of lower quality and contain a lot of measurement errors. But their high density in urban areas can be of advantage in post-flood analysis, provided that the bad ones can be automatically detected and removed. The collection and processing or citizen rain gauge data is part of an ongoing research project at TUD and the topic of a MsC thesis in collaboration with KNMI (kickoff in October 2017).

<u>Sweden:</u> The city of Stockholm operates a network of 11 tipping-bucket rain gauges covering an area of approximately 100 km² around Stockholm (Fig. 1). The network has been in place since the year 2000. The gauges have a tipping resolution of 0.2 mm. In MUFFIN, observations from the station network are used primarily for evaluating precipitation estimates from radar observations (HIPRAD) in the same area (Fig. 1). Both types of observations are used in the development of the HYPE model for high-resolution application in urban environments. On a national scale, precipitation and wind observations from the network of meteorological stations are used to generate the PTHBV data base (Precipitation and Temperature for the HBV model). The PTHBV data base contains daily gridded gauge-based observations at 4x4 km² resolution, obtained by optimal interpolation taking altitude and wind into account. PTHBV is used to produce the gauge-adjusted HIPRAD precipitation

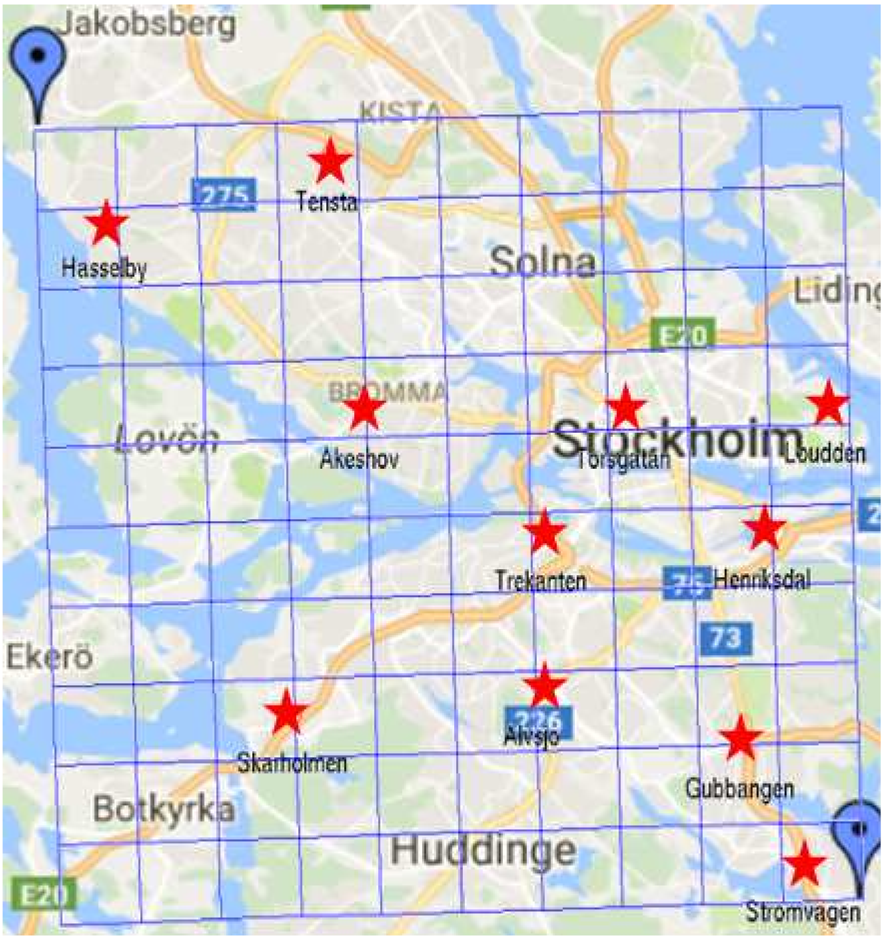

Figure 1: Municipal precipitation station network in Stockholm (stars) and

product (see 2.2 below).

<u>Finland:</u> Aalto University operates 3 co-located high-resolution fully automatic tipping-bucket rain gauges of type Decagon ECRN-100 in the Länsi-Pakila

catchment. The gauges provide on-site rainfall measurements for the snow-free periods of 2017 and 2018 at 1 min temporal resolution and 0.2 mm tipping resolution. They are installed on the roof of a low-level retirement home about 1 m apart from each other without wind shields. No quality control is performed. Outputs are generated in text format and available upon request. In addition to that, the Finnish Meteorological Institute FMI provides open continuous measurements of temperature, radiation, relative humidity, wind and precipitation at 10 min temporal resolution (1 min for Helsinki-Vantaa airport). The rainfall sensor is a OTT Pluvio 2 with wind shield. There are 4 weather stations within a distance of 10 km from the catchments used within MUFFIN. Data are available at https://en.ilmatieteenlaitos.fi/open-data.

Denmark: the Water pollution committee (WPC) provides rainfall data from a national network of tipping bucket rain gauges with 0.2 mm tipping resolution. Tipping times are provided with a precision of 1 min but the data storage format makes it impossible to distinguish between dry periods and missing values. The oldest rain gauge from the network dates back to 1979. A total of 7 WPC gauges are covering the Østerå catchment with historical data going back to the late 1990's. Approximately 1.7 km from the project area, there is a parking lot equipped with a disdrometer and 9 tipping bucket rain gauges with data going back to 2013 (Ahm and Rasmussen, 2017, http://vejrradar.dk/beware/). In addition, 73 WPC gauges covering an area of approximately 65 km x 40 km in the greater Copenhagen region are used to produce the long-term forcing dataset for the HYPE model within the framework of the joint experiments (see Section 2.3). This region has been selected because it offers the largest rain gauge density in Denmark.

Europe: Precipitation observations from some 7000 meteorological stations in Europe are used in the production of the E-OBS data set. E-OBS contains daily maps of gridded data spanning the period from 1 January 1950 to the present. The E-OBS data set was developed as part of the ENSEMBLES project, with the aim to provide data for the validation of Regional Climate Models (RCMs) and also for climate change studies. The data used in the gridding of E-OBS is from the European Climate Assessment & Dataset (ECA&D, https://www.ecad.eu/). ECA&D is a collection of daily station observations of currently 12 elements (of which five are gridded) and contains data from nearly 6600 European stations (status in June 2012) and is gradually expanding. The E-OBS data set was derived through a three stage process. Monthly precipitation totals were first interpolated to a rotated pole 0.1 degree latitude by longitude grid using three-dimensional (latitude, longitude, elevation) thin plate splines. Daily anomalies, defined as the departure from the monthly total precipitation, were interpolated to the same 0.1 degree grid, and combined with the monthly mean grid. Indicator kriging has been used to interpolate daily anomalies, where the state (wet/dry) of precipitation was first interpolated, after which the magnitude at "wet" 0.1 degree grid points was interpolated using universal kriging. Finally, the 0.1 degree points have been used to compute area-average values at the four E-OBS grid resolutions (0.25 and 0.5 degree regular latitude-longitude grid and

0.22 and 0.44 degree latitude-longitude rotated pole grids). Recently, a near real-time version of E-OBS has been developed. In MUFFIN, E-OBS will be used to gauge-adjust the pan-European OPERA radar precipitation composites.

2.2. Weather Radars

A large amount of historical and real-time weather radar data is being collected within MUFFIN. Most of it comes from horizontally scanning C-band and X-band radars. On top of that, TU Delft also operates a vertically scanning micro-rain radar (MRR). The radar data are primarily used to get insight into the spatial and temporal distribution of rainfall before, during and after the flood. A few minutes or hours before the flood, radar data are used to generate short-term rainfall forecasts (i.e., nowcasts) based on Lagrangian persistence. During the flood, radar provides situation awareness for water managers and emergency responders eager to know which areas are most affected. After the flood, radar data are combined with ground observations to provide total rainfall accumulation maps, highlight damage hot spots and perform post-flood assessment.

Domain	**Product**	**Resolution**	**Availability**
Netherlands	KNMI real-time national radar reflectivity and rain rate composites	5 min, 1 km	2017 - present
Netherlands	KNMI national gauge-adjusted radar composites	3 h, 1 km	2010 - present
Rotterdam	Rotterdam X-band radar	1 min, 100 m	2017 - present
Rotterdam	Micro-rain radar	10 s, 100 m	2017 - present
Sweden	SMHI real-time national radar reflectivity and rain rate composites	15 min, 2 km	2000 - present
Sweden	SMHI national gauge-adjusted radar composites (HIPRAD)	15 min, 2 km	2000 - present
Finland	FMI Open weather radar data	5 min, 500 m	2015 - present
Helsinki	University of Helsinki Capital area radar composite	1 min, 250 m	Upon request
Aalborg	DMI C-band radar	10 min, 2 km	2010 - present
Aalborg	2 X-band radars in Aalborg	1 min, 100 m	2014 - present
Europe	OPERA radar composite	1 h, 2 km	2011 - present
World	GPM IMERG	30 min, 0.1 deg	2014 - present

Netherlands: The Royal meteorological institute (KNMI) provides near real-time radar rainfall composites at 1x1 km spatial resolution and 5 min temporal resolution for the entire country. These composites are obtained by combining the data from 2 national C-band radars at different at different elevation angles. In addition to the real-time radar rainfall estimates, KNMI also provides radar rainfall nowcasts for lead times of 5 min up to 2 hours in steps of 5 minutes. These are based on Lagrangian extrapolation of radar echos along the apparent direction of motion (inferred via optical flow). The historical radar data are freely available on the KNMI website (https://data.knmi.nl/datasets). The nowcasts are available upon request to KNMI or TU Delft. In addition of the national C-band radars, the city of Rotterdam installed a X-band fully polarimetric weather radar from Metasensing (https://www.metasensing-group.com/). The radar, installed in summer 2017, is located in the city centre of Rotterdam, near the central train station, on the roof of one of the highest buildings in Rotterdam. It scans horizontally at 1 round per minute with a range resolution of 30m. Most of the development of the radar, in particular the software for converting the raw measurements to quantitative rainfall estimates is done by a startup called SkyEcho (http://www.sky-echo.eu/), which was built by former TU Delft researchers. Unfortunately, the radar got damaged in January 2018 during a big wind storm and is currently offline. TU Delft also operates another X-band weather radar called IDRA (http://ftp.tudelft.nl/TUDelft/irctr-rse/idra/). This radar is located on the top of a weather tower in Cabauw, a supersite for atmospheric observation in the Netherlands approximately 30 km East of Rotterdam. Finally, a small micro-rain radar (MRR) by Metek (http://metek.de/) has been installed on the roof of the Civil Engineering building at TU Delft. The radar points vertically, collecting time-height profiles of reflectivity, rainfall rates, liquid water content and raindrop size distributions with a resolution of 30 m and 10 s. The instrument is mostly used to study the vertical variability of rainfall and microphysical processes from the clouds down to the ground.

Sweden: Radar data are available from the NORDRAD (NORDic weather RADar network) radar composite, based on measurements from 12 radars in Sweden. The original resolution of the composite is 2x2 km^2, and the temporal resolution is 15 min. Although the NORDRAD product contains several corrections to the radar echoes, such as beam blockage, systematic range dependent bias and removal of false precipitation regions according to satellite images, there are still errors which are clearly visible at longer accumulation intervals. To obtain a product more applicable in hydrological simulation, a mixture of the PTHBV gridded observations and the NORDRAD composite was developed. The new product called HIPRAD (HIgh-resolution Precipitation from gauge-adjusted weather RADar) uses the transient 1-h information of NORDRAD, but scales it with the monthly accumulations of PTHBV, such that systematic errors in the radars are removed. In MUFFIN, HIPRAD data are used in the development of the HYPE model for high-resolution application in urban environments.

Denmark: In collaboration with Aalborg Water Utilities, Aalborg University operate two dual polarimetric X-band doppler radars. Aalborg university has developed quality controlled and bias adjusted QPE and QPF products, which are available in real-time for both both the Østerå and Kærby catchments. Furthermore, DMI operates a dual polarimetric C-band doppler radar located approx. 50 km north of Aalborg. This has the benefit of a much larger range (240 km), but also a coarser resolution. In

MUFFIN this radar will in combination with X-band radars be used to provide nowcasts with a lead time of up to two hours.

Finland: The FMI provides real-time open weather radar data composites from 10 national C-band radars at a resolution of 5 min and 500 m (https://en.ilmatieteenlaitos.fi/open-data). The radar data undergo 5 standard signal processing steps: a) removal of stationary targets, b) adjustment of the weakest and strongest signals according to the radar, c) correction for the effects of the vertical profile of reflectivity, d) removal of non-meteorological targets and e) conversion from radar reflectivity to rain intensity based on a Z-R power-law. Products are available in GeoTIFF format. The nearest radar (Vantaa) is located approximately 5 km from the studied catchments. The Capital Area Radar Composite is a custom 1 min, 250 m Cartesian product generated by the radar group of the University of Helsinki. It combines data from 3 state-of-the-art C-band dual polarization radars in Kumpula (KUM), Vantaa (VAN) and Kerava (KER) and is available in Matlab data array or GeoTIFF format. The multi-radar setup mitigates some of the problems common to rainfall estimation in urban areas, such as increased resolution and accuracy, especially at lower elevation angles. The high temporal resolution is achieved by applying an advection interpolated scheme based on the optical flow algorithm. The product has recently been upgraded to take advantage of dual-polarization measurements.

Europe: Odyssey, the OPERA Data Centre (http://eumetnet.eu/activities/observations-programme/current-activities/opera/), generates and archives composite products from raw single site radar data using common pre-processing and compositing algorithms. Odyssey creates 3 composite products: instantaneous surface rain rate, instantaneous max reflectivity and 1-h rainfall accumulation. In the surface rain rate composite each composite pixel is a weighted average of the lowest valid pixels of the contributing radars, weighted by the inverse of the beam altitude. Polar cells within a search radius of 2.5 km of the composite pixel are considered. Data measured below 200 m altitude are not used. Measured reflectivity values are converted to rainfall (mm/h) using the Marshall-Palmer equation. Rainfall accumulation is simply the sum of the previous four 15-minute surface rain-rate products. In MUFFIN, the ability of the OPERA composites to describe rainfall events of different character will be assessed. Further, gauge-adjustment using the E-OBS data will be tested, with a procedure similar to the one used for HIPRAD in Sweden.

2.3. Common precipitation forcing dataset

Within the framework of the joint experiments, a common long-term precipitation forcing dataset has been produced. This was done on the basis of data collected by a dense rain gauge network operated by the Danish water pollution committee. The network is comprised of 73 gauges over an area of 65 km x 40 km in the greater Copenhagen area. Data records go back to 1979 (15 gauges) with most of the time series starting in 1999. The collected data are used to generate a time series of gridded precipitation fields of size 62 x 38 km, at 1x1 km spatial resolution at 1 hour temporal resolution. The generated fields are primarily intended to be used as input into the HYPE model. Each field is generated using the linear interpolation method known as “simple kriging”. The autocovariance function used for the interpolation is assumed to be a spherical model, with nugget set to zero and variable sill and range values depending on the observations at each time step. The gridded precipitation fields are outputed in ASCII format for each year between 1979 and 2017. The zipped data and grid cell coordinates can be downloaded for free at https://surfdrive.surf.nl/files/index.php/s/s9P9caJiHHpKKYb

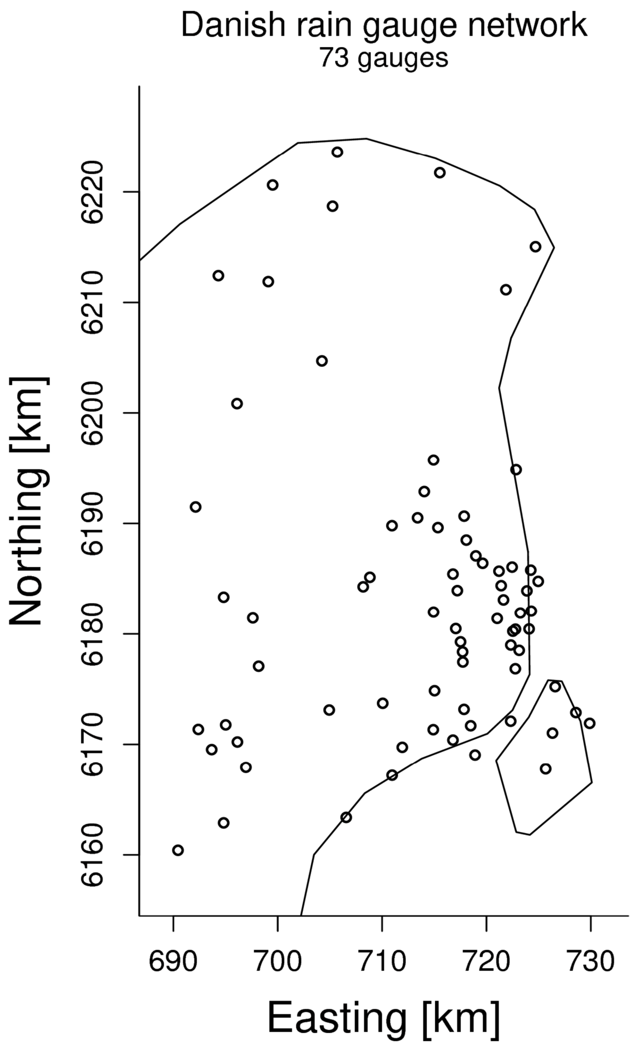

Figure 2: Rain gauge network in the greater Copenhagen area

In addition to the long-term gridded interpolation dataset, the same Danish rain gauge network was used to simulate random realizations of individual events at higher spatial and temporal resolutions. These are used to study the models’ responses to extreme rainfall events at different spatial and temporal resolutions. These fields are not interpolated but simulated using a technique known as “sequential Gaussian simulation” (SGS). Their particularity is that the simulations reproduce observed rainfall values at the gauge locations while the rest of the domain is filled with randomly drawn values from the locally estimated conditional distribution of rainfall. Due to the random nature of the simulations, each individual realization looks different. But the overall spatial autocovariance structure of the rainfall is the same for all realizations. The main advantage of such a technique is that it produces rainfall fields which are less smooth and more realistic in terms of extremes than interpolated values.

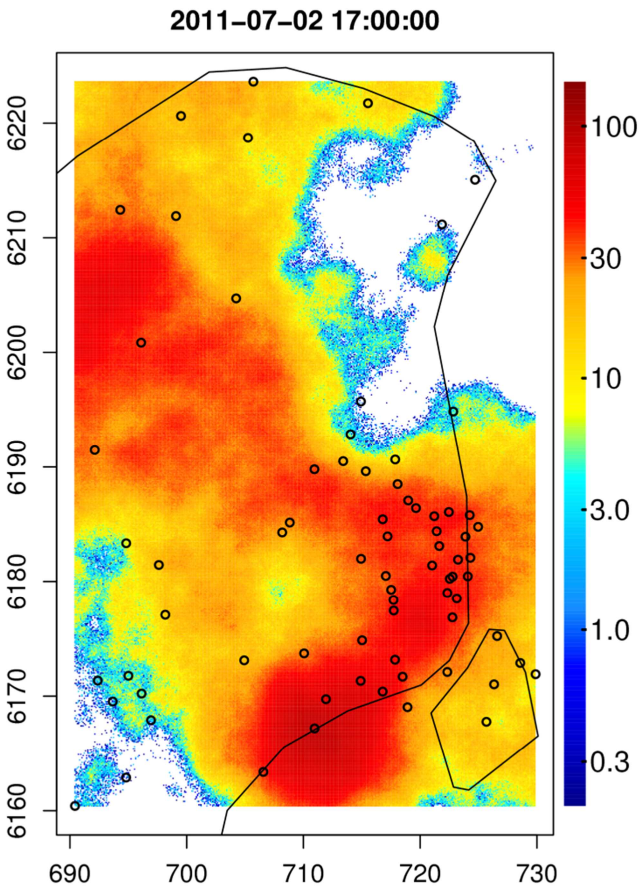

Figure 3: Example of simulated rainfall field at 100x100m resolution

3. Forecasts and Simulations

Domain	Product	Resolution	Lead time	Availability
Netherlands	WRF Simulations	15 min, 100 m	0 - 72 h	Selected events only
Netherlands	HARMONIE model outputs	1 h, 2.5 km	0 - 48 h	2015 - present
Netherlands	KNMI national C-band radar nowcasts	5 min, 1 km	0 - 2 h	2017 - present
Netherlands	Rotterdam X-band radar nowcasts	1 min, 100 m	0 - 15 min	Upon request
Scandinavia	Hybrid NWP nowcasting KNEP	1 h, 2.5-11 km	0 - 56 h	2012 - present
Scandinavia	HARMONIE-AROME Ensemble forecasts MEPS	1 h, 2.5 km	0 - 56 h	2016 - present
Finland	AALTO STEPS ensemble C-band radar nowcasts	5 min, 500 m	0 – 6 h	Upon request
Denmark	AAU ensemble X-band radar nowcasts	1 min, 100 m	0 - 30 min	Upon request
Denmark	AAU ensemble C-band radar nowcasts	10 min, 2 km	0 - 2 h	Upon request
Denmark	DMI-HIRLAM	1 h, 3 km	0 – 24 h	Upon request
Europe	ECMWF HRES	1h, 9 km	0 – 10 days	Upon request

Netherlands: KNMI provides HARMONIE model outputs and weather forecasts at a spatial resolution of 2.5 km for lead times up to 48h. In addition, TU Delft has set up its own version of the Weather Research and Forecasting software (WRF 3.9) over the Netherlands. The WRF model can be used to perform high-resolution numerical weather modeling and forecasting for selected rainfall events over Rotterdam. The WRF model is set up to have a parent domain of 5 km grid spacing covering the BeNeLux region, a second domain of 1 km grid spacing over the Netherlands and a third innermost domain over Rotterdam at 200 m grid spacing and 135 vertical levels. Both single- and double-moment microphysics schemes have been implemented and results compared against a network of radar and rain gauge observations. In August 2017, 500,000 computing hours were allocate for this on the Cartesius HPC system. Still, given the size of the domain and the high-resolution, only selected events can be simulated using this method.

Scandinavia: Two types of high-resolution forecast products covering Scandinavia (Fig. 4) are issued operationally at SMHI. One product is the HARMONIE-AROME ensemble forecasts called MEPS. These comprise 1 control and 10 members with resolutions 1 h (56 h ahead) and 2.5 km. They have been archived since 2016 (with some gaps). The other product is a NWP-nowcasting hybrid called KNEP. The first hour in this forecast is pure nowcast and the seventh hour is pure NWP; in between the source are blended in a weighting scheme, going from most weight on the nowcast in hour 2 to most weight on NWP in hour 6. The resolutions are the same as for MEPS, but KNEP is deterministic. KNEP has been archived since 2012 and in this period the spatial resolution has increased from 11 km to 2.5 km.

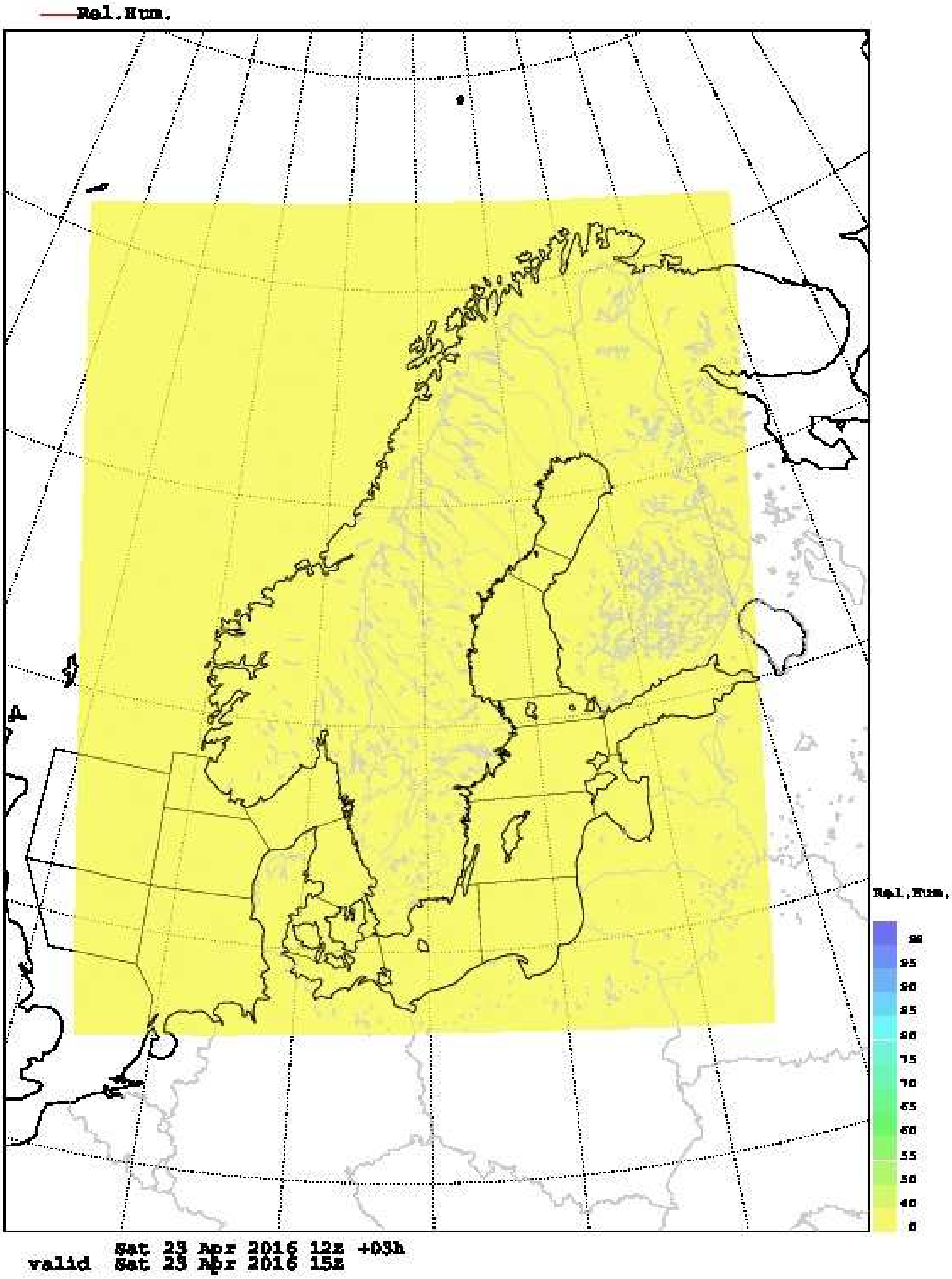

Figure 4: Output domain of forecast products KNEP and MEPS

Denmark: Aalborg University has developed a radar nowcast ensemble model for both its X-band and C-band radar data. The model can be set up to run in real time with relevant input data. It is possible to request NWP data from DMI for the HIRLAM-S03 model covering Denmark with a spatial resolution of 3 km, hourly updates and lead times of up to 24 hours.

Finland: Aalto University is currently setting up the STEPS (Short Term Ensemble Prediction System) model to produce short-term radar rainfall ensemble nowcasts for the Helsinki region. STEPS works by advection-extrapolating the radar observations into the near future (i.e., up to a few hours ahead) based on radar data and outputs from numerical weather prediction models. The precipitation ensembles are generated by blending the advection-extrapolated radar data with synthetic scale-dependent noise fields whose properties are determined by applying a multiplicative cascade-based scale decomposition scheme on the latest available data. Several noise generators and advection schemes can be used. In the case of Aalto, the three-radar Capital Area Radar Composite quantitative precipitation estimates produced by the University of Helsinki and the FMI operational radar data will serve as high-resolution input data for the STEPS model.

Europe: On the pan-European scale, we have access to forecasts from the ECMWF HRES system (European Centre for Medium-range Weather Forecasting High RESolution model). These 10-day forecasts are deterministic with resolutions 1 h and 9 km, but HRES is produced in the ensemble forecasting system of ECMWF. For the medium-range forecasts an ensemble of 52 individual ensemble members are created twice a day. One member is at a higher spatial resolution than the other members (called the HRES at ECMWF), its initial state is the most accurate estimate of the current conditions and it uses the currently best description of the model physics. The HRES provides a highly detailed description of future weather and averaged over many forecasts it is the most accurate forecast for a certain period, which is currently estimated as 10 days for large scale properties of the atmosphere. However for any particular forecast it may not be the most skillful member of the ensemble. Also when viewed in isolation it cannot provide an estimate of forecast uncertainty or confidence.